Defense Technical Information Center Compilation Part Notice

ADP014319

TITLE: Magnetoresistance and Hall Effect Characterisation on Magnetic Thin Films Multilayers

DISTRIBUTION: Approved for public release, distribution unlimited

This paper is part of the following report:

TITLE: Materials Research Society Symposium Proceedings. Volume 746. Magnetoelectronics and Magnetic Materials - Novel Phenomena and Advanced Characterization

To order the complete compilation report, use: ADA418228

The component part is provided here to allow users access to individually authored sections of proceedings, annals, symposia, etc. However, the component should be considered within the context of the overall compilation report and not as a stand-alone technical report.

The following component part numbers comprise the compilation report:
ADP014306 thru ADP014341

Mat. Res. Soc. Symp. Proc. Vol. 746 © 2003 Materials Research Society R5.5

Magnetoresistance and Hall Effect Characterisation on Magnetic Thin Films Multilayers

Jenica Neamtu[1] and Marius Volmer
Transilvania University, 29 Eroilor, Brasov 2200, Romania
[1]Research and Development Institute for Electrical Engineering, 313 Splaiul Unirii, Bucharest, Romania

ABSTRACT

We have performed both Hall effect, and magnetoresistance measurements on thin films of Permalloy (Py 10 nm) and Py(t_{Py})/Cu(t_{Cu})/Py(t_{Py}) multilayers deposited on thermally oxidized Si substrates, where t_{Py}=4 and 10 nm and t_{Cu}=4 and 8 nm. The measurements were made at room temperature in a setup that allows us to perform both Hall effect and magnetoresistance measurements. The Hall effect measurements were performed varying the angle, $\Delta\theta$, between the magnetic field direction and the normal to the film plane from 0 to 90 degrees. The measured voltages present hysteresis loops at low magnetic field even for $\Delta\theta=0°$. From these measurements we can obtain some information regarding the magnetic properties of our samples.

INTRODUCTION

Multilayered structures consisting of ferromagnetic layers separated by a nonmagnetic, conducting or insulating, spacer are very attractive for development of magnetic sensors and data storage techniques. Such structures can exhibit anisotropic magnetoresistance (AMR) and giant magnetoresistance (GMR) effects and these two give the total magnetoresistance (MR) effect. The AMR effect leads to the 'pseudo-, or planar Hall effect' (PHE) [1] which has the following two characteristics: (i) The output voltage measures an electric field that is perpendicular to the applied current; and (ii) the magnetic field vector lies in the plane of the current and voltage electrodes. The field dependence of the Hall effect becomes more interesting when the applied magnetic field is out of the film plane. In this paper we show the good sensitivity of the PHE signal which can be, together with MR measurements, a useful technique for thin films characterization. To achieve this goal we present the dependence of the PHE as a function of the field at different out of planes angles and discuss the origin of the hysteresis. To complete this discussion we used a micromagnetic simulator [2] to calculate the hysteresis loop of the sample. The results are related with the samples microstructure.

EXPERIMENTAL DETAILS

Thermally evaporated Py thin films and Py/Cu/Py multilayers (MLs) were deposited on to oxidized Si substrates at room temperature. Here Py denotes permalloy ($Ni_{80}Fe_{20}$). Two types of samples were obtained by this method: Si/SiO_2/Py(10 nm) thin films and Si/SiO_2/Py(t_{Py})/Cu(4 nm)/Py(t_{Py}) magnetic multilayers with t_{Py}=4 and 10 nm. The local surface topography was studied using atomic force microscopy (AFM). The magnetization measurements have been performed at room temperature using a vibrating sample magnetometer (VSM). Resistance is measured in a four-point contact geometry with the contacts in line or forming a square of approximately 5 mm each side. This last setup, presented in figure 1, allows us to perform both magnetoresistance and Hall effect measurements.

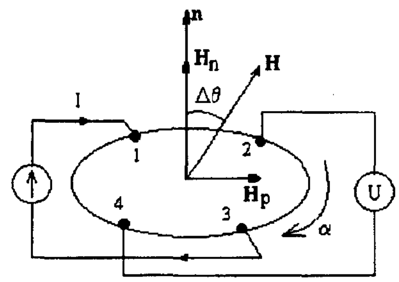

Figure 1. Schematic diagram of the connections used in the planar Hall effect experiments. Also shown are the definitions of some of the angles used in the discussion. Here, the angle between the current direction, I, and the in plane magnetic field, $\mathbf{H}_p$, is α=45º.

H is the applied magnetic field which makes the angle $\Delta\theta$ with respect to the surface normal **n**. We denote with $\mathbf{H}_p$, the in plane component of **H** and with $\mathbf{H}_n$ the component of **H** which is normal to the sample plane. To maximize the PHE values in these films, the in plane component of the magnetic field ($\mathbf{H}_p$) has to be applied at an angle α=45º to current direction, as shown in figure 1. In some cases the samples were rotated back (α=0º) in order to minimize the influence of the AMR effect on the Hall effect measurements. In this case the current, I, is parallel to $\mathbf{H}_p$.

DISCUSSION

The AFM topography for a 4 nm permalloy thin film deposited on to oxidized Si substrate reveals a rough surface with a rms-roughness of 1.1 nm. The maximum height of the surface roughness was about 10.7 nm. This is a characteristic for evaporated thin Py layers [3,4]. During the first stage of Py deposition, isolated Py islands are formed on the surface. The percolation occurs at Py thickness of about 2 nm when the samples are deposited on to Si/SiO_2 substrates [4]. These facts suggest that the Py(4 nm)/Cu(4 nm)/Py(4 nm) sample presents distortions of the multilayer structure and intermixing between permalloy and Cu layers. The predominant conduction mechanism is diffusive scattering at interfaces, grain boundaries and defects that alter the MR and Hall effects. The MR ratio found is no grater than 0.08 %. When the Py thickness increases the film becomes uniform in microstructure. For a Py(10 nm)/Cu(4 nm)/Py(10 nm) ML, the average roughness is very low, 0.87 nm. The average grain size, D, is about 15 nm. The Hall resistivity is about four times grater than for the ML with t_{Py}=4 nm. For these reasons thermally evaporated MLs with very thin Py layers are not interesting for practical applications.

When the thickness of the magnetic film is grater than 5 nm the spin-dependent scattering of the electrons takes place predominantly in the bulk of the magnetic layers and the galvanomagnetic properties are close related with the magnetic properties [5]. We present, in figure 2, the $R_l(H)$ curve (longitudinal MR effect) and the corresponding hysteresis loop of a Py(10 nm) thin film. The magnetization loop was calculated from the MR measurements assuming a quadratic dependence between the MR effect and the thin film magnetization.

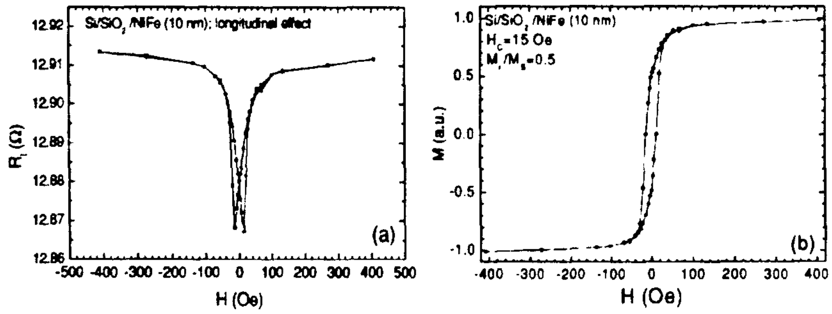

Figure 2. (a) Resistance as function of the applied magnetic field and (b) the corresponding hysteresis loop for an evaporated Py(10 nm) thin film when the applied magnetic field is parallel with the current direction

On the other hand we have simulated the magnetization curve using a collection of 12x12 single domains of Permalloy. Each single domain is an island 10 nm thick and 95 nm each side. The distance between the adjacent domains is 5 nm. This model was inspired from the film structure. The calculations were made using the micromagnetic simulator SimulMag [2]. The results of this simulation are in good agreement with other experimental data [4], for the remnant-to-saturation magnetization ratio $M_r/M_S \approx 0.71$, and with the MR measurements for the value of the coercive field, H_C=15 Oe. Also we can see the domains structures in the demagnetizing state. The spin structure for the coercive field, H_C, and the magnetization curve, when the magnetic field is applied in the film plane, are shown in figure 3.

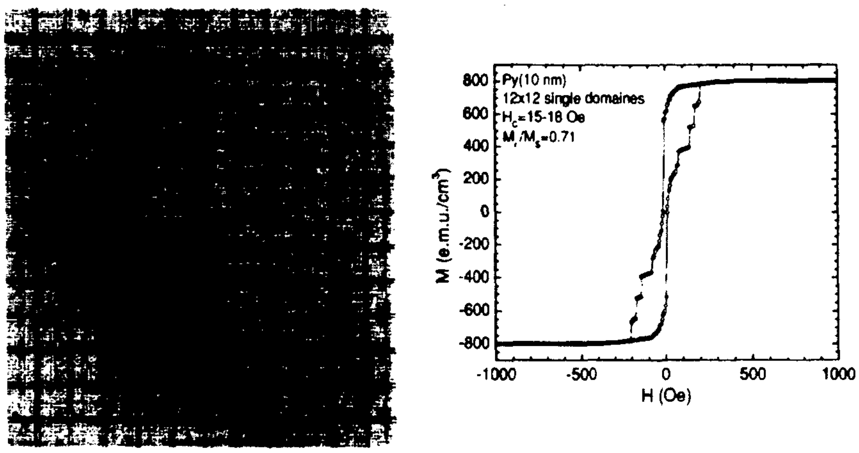

Figure 3. The results of the micromagnetic simulation for an evaporated Py(10 nm) thin film. The magnetic field is applied in the film plane.

The magnetization curves of the Py(10 nm)/Cu(4 nm)/Py(10 nm) multilayer deposited by high vacuum evaporation displayed typical characteristics of ferromagneticaly coupled multilayers. The GMR effect is less than 0.05 %. The AMR effect ratio is about 0.5 %. This value is much smaller than the AMR ratio in bulk samples. There are some effects that may contribute to this difference. First, the ML studied may be structurally less well-defined leading to additional electron scattering at grain boundaries and other defects. Second, diffusive scattering at the outer boundaries of the film (dimensionality effect) may affect the AMR ratio. Third, the Cu interlayer may play a shunting effect. Again, using the MR data we obtained the magnetization curve shown in figure 4(a).

To simulate the magnetization curve we used two Py layers each consisting in a collection of 10x10 single domains of permalloy. Each single domain is 10 nm thick and 95 nm each side. The distance between the adjacent domains is 5 nm. Again, the model was inspired from the film structure. The distance between the two layers is the interlayer thickness, t_{Cu}=4 nm. Now we have to estimate the ferromagnetic interlayer coupling. It was shown [6] that the dependence of the coupling constant J on the Cu-layer thickness, for t_{Cu}>1.5-2 nm, is well described by the Néel model for magnetostatic interlayer coupling, based on the interaction between the dipole fields produced by rough interfaces:

$$J = \frac{\pi^2}{\sqrt{2}} \frac{h^2}{\lambda} \mu_0 M_S^2 \exp\left(\frac{-2\pi\sqrt{2}t_{Cu}}{\lambda} \right) \tag{1}$$

Here, λ and h are the lateral length scale and amplitude of the roughness, respectively, and M_S is the saturation magnetization (M_S=800 kA/m or 800 emu/cm^3 in CGS). In this model the roughness is assumed to be two-dimensional and sinusoidal. Here, λ is determined by the grain size. From AFM measurements [3] we have h=1.35 nm and λ=15 nm. If we consider t_{Cu}=4 nm the interlayer coupling is J=0.23 mJ/m^2. For this value the coupling field is H_0=2457 A/m (31 Oe). This value is correct only if we consider the magnetic layers completely separated by the Cu spacer. Because of the Py bridges that exists trough the spacer the coupling may have local variations that exceed 31 Oe. Between the top and the bottom layers we introduced coupling fields that have random values from 30 to 60 Oe. The results of our calculations using the micromagnetic simulator SimulMag are presented in figure 4(b).

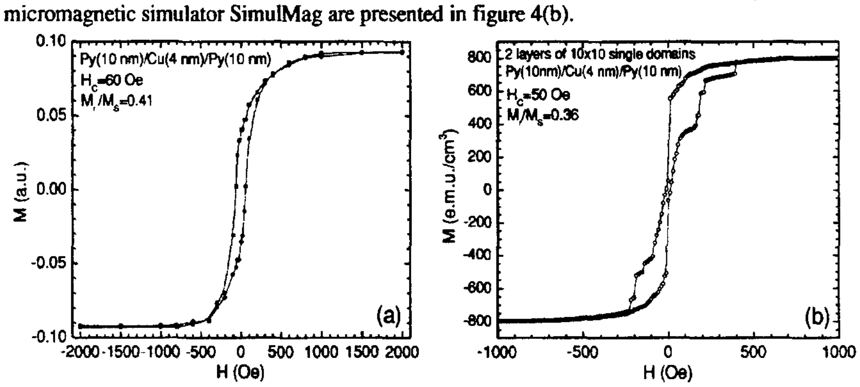

Figure 4. (a) The magnetization curve calculated for an evaporated Py(10 nm)/Cu(4 nm)/Py(10 nm) multilayer from the MR data. (b) The micromagnetic simulated magnetization curve.

We obtained a good agreement between the measured curve [3] and the calculated curves for the coercive field and the remnant-to-saturation magnetization ratio values. For our ML the ratio $M_r/M_S \approx 0.4$ is smaller than the value $M_r/M_S \approx 0.7$ obtained for a Py(10 nm) layer. This can be explained by the fact that in low (or zero) magnetic field the spins from the two magnetic layers start to rotate in a manner to minimize the total free energy.

Using a setup presented in figure 1, we performed Hall effect measurements both on Py and Py/Cu/Py ML. In what follows we present, in figure 5, the results obtained for thermally evaporated Py(10 nm) layer. In figure 5(a) are shown the field dependencies of the output voltage, U, for different angles $\Delta\theta$ between the applied field, **H**, and the perpendicular to the film plane **n**. Here $\alpha=45^\circ$ to maximize the AMR effect. We can see, in insert, the hysteretic behavior at low magnetic field for $\Delta\theta=0^\circ$. It is interesting to note that U(H=0) takes the same values, in figure 5(a), for different orientations $\Delta\theta$ of the sample. This means that the remnant magnetization of the thin film takes the same values. This assumption can be illustrated by a simulation of the remnant magnetization state of the film starting from the saturated state for different values of $\Delta\theta$ varying from 0.5° to 90°. The result of our simulation is presented in figure 5(b). Using these observations we were able to extract the contribution of the AMR effect from the measured voltage and to obtain the field dependencies of the Hall voltages for different angles $\Delta\theta$. Such dependencies are shown for $\Delta\theta=0^\circ$, in figure 5(c) and for $\Delta\theta=5^\circ$, in figure 5(d).

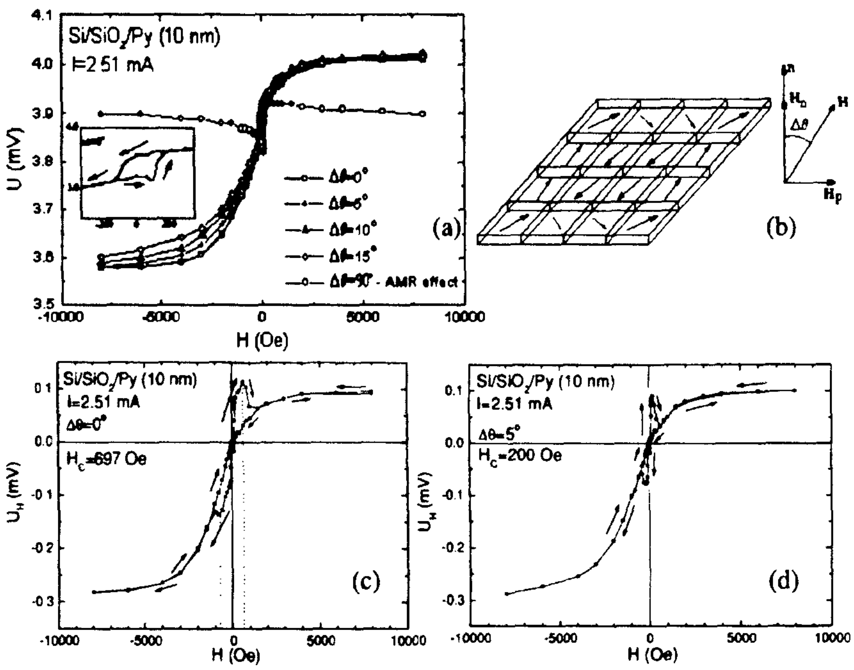

Figure 5. Field dependencies of the output voltage, U, and the Hall voltage, U_H, for different angles $\Delta\theta$ between the applied field, **H**, and the perpendicular to the film plane, **n**. The arrows are guides for the eyes.

The asymmetry between the positive and negative field regions is probably due to some other in-plane magnetoresistive effects like the asymmetry of the AMR effect as we can see from figure 5(a). The sharp "anomalies" of the Hall voltage, which appear in figure 5(c-d), can be connected with the reversal processes that take place in the film plane which produce a jump of the AMR ratio. With H_C we denote the critical values of the field for which the magnetization reversal takes place in the film plane. Now, we can make some assumptions regarding the reversal processes that take place in the film. For $\Delta\theta=0°$ we see, in figure 5(c), a relatively large transition region. This suggests a reversal process mainly due to domain wall motion. As $\Delta\theta$ increases the width of the transition regions decreases as we can see from figure 5(d). For $\Delta\theta>10°$ the magnetization reversal will take place mainly by coherent rotation. This is natural because of the relatively large values of the in plane component of H. For $\Delta\theta=10°$ we obtained $H_C=108$ Oe and for $\Delta\theta=15°$ we have $H_C=77.3$ Oe. The same discussion can be made for the Py(10nm/Cu(4 nm)/Py(10 nm) ML. We found an increase of the H_C values relative to the Py film which is due to a positive coupling between the ferromagnetic layers. This is the case of the non-flatness layers [3,4,6]. The values of H_C (20 Oe for Py and 60 Oe for the Py/Cu/Py ML), when H lies in the film plane ($\Delta\theta=90°$), are in very good agreement with the values measured using a VSM.

When $\alpha=0°$ (in figure 1) the Hall effect measurements show the usual behavior because the influence of the AMR effect on the measured voltage is minimized. The saturation field obtained for our ML, when the magnetic field is applied normal to the film plane is $H_S\approx6000$ Oe. This value is less than the value predicted from the shape anisotropy ($H_{S0}=4\pi M_S=10.5$ kOe) known for flat surfaces, but is consistent with the film surface topography [4]. This reduction of the perpendicular anisotropy can be explained by a large interface roughness which reduces the dipolar energy anisotropy and leads to a roughness effect [4] of about 5 nm for our MLs evaporated at RT on to oxidized Si substrates. These results are in good agreement with the AFM measurements and explain the absence of the AF coupling between the adjacent Py layers.

CONCLUSIONS

We used MR and Hall effect measurements to investigate the magnetic properties of the thin films and magnetic multilayers. Precise MR and Hall effect measurement can allow us to obtain some useful information about the magnetization curve and the reversal mechanism. The absence of the GMR effect in evaporated Py/Cu multilayers is caused by a rough interface. Using a micromagnetic simulator we were able to obtain the magnetization curves considering the film microstructure and material parameters.

REFERENCES

1. F.Y. Ogrin, S.L. Lee, Y.F. Ogrin, J. Magn. Magn. Mater. 219 (2000) 331
2. John O. Oti, SimulMag Version 1.0, *Micromagnetic Simulation Software*, User's Manual, Electromagnetic Technology Division, National Institute of Standards and Technology Boulder, Colorado 80303, December 1997
3. J. Neamtu, M. Volmer, A. Coraci, Thin Solid Films 343-344 (1999) 218
4. T. Lucinski, G. Reiss, N. Mattern, L. van Loyen, J. Magn. Magn. Mater. 189 (1998) 39
5. Y. Gondo, Y. Suezawa, Thin Solid Films 281-282 (1996) 496
6. J.C.S. Kools, Th. G.S.M. Rijks, A.E.M. De Veirman, R. Coehoorn, IEEE Trans. Magn., **31**, 3918 (1995)